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ILLUMINATING ENGINEERING SOCIETY

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Presidential Address

By W. R. STEVENS, B.Sc. *(Fellow).*

"Passim Spargere Lucem"

A few months ago the Society adopted a motto. In it, expressing its purpose "To Spread Light Everywhere," we accept the two-fold responsibility of lighting "things" and of enlightening people. Implicit, too, is the desire to improve the standard of lighting.

A newly appointed President does not often have a subject for his address so opportunely presented, and my main theme is that of all the many ways in which the Society attempts to fulfil the promise of its motto, the most important is that of helping its members to help themselves. This is a familiar theme, but it is no less important because of that. It needs reiteration whenever we ask ourselves "What does the Illuminating Engineering Society stand for?" and "Why do I belong to it?"

I take it as axiomatic that we wish to see "better lighting" even though we are not always able to say what is "better." Presumably we not only wish to make the best use of the knowledge and apparatus available to us for each and every lighting installation, but we wish to improve these facilities.

How are such improvements likely to come about? It may be that nuclear fission will provide us with a much cheaper source of energy than we have at present, and this could lead to a revolution in lighting methods: but as lighting engineers we can only wait and hope. Therefore, although it is interesting to speculate on what might happen if electrical energy cost, say, one-tenth of what it does at present, I shall not now devote any further time to the possibility.

Turning to matters more in our control, there are three main springs from which new ideas in lighting may well up, and we will examine each of them in turn. They are:—

(i) The study of light sources and the production of new ones;
(ii) The study of seeing and the properties of the eye; and
(iii) The study of lighting installation design.

The Study of Light Sources

With one exception the great upsurges of interest in artificial lighting have followed the introduction of new light sources. The exception occurred during the last war and even this may be attributed as much to the tubular fluorescent lamp as to the reaction from blackout.

The work of the chemist and physicist on sources has, therefore, been the mainspring of lighting, and in recent years at least application engineers have never fully worked out one source before another has appeared. Not surprisingly, men were slow to appreciate at first what these new sources could mean to everyday life. A century of dormancy lay between Clayton's demonstration of the luminous coal gas flame and Murdoch's application of it in 1792. But once its value was realised this new source of light spread rapidly and when, after yet another hundred years, Welsbach produced the incandescent mantle his invention was soon applied.

By this time the electric filament lamp had come into existence and was being installed by the daring and the far-sighted. It had to make headway against an already well-organised gas supply, but increasingly electricity showed itself to be the ideal source of energy for producing artificial light.

Then, in 1931, the first practical electric discharge lamps were introduced.

Presented at a meeting of the Society held in London, October 13, 1953.

The response of designers was immediate. Within a year or two, in spite of the fact that the new sources presented very different problems of design from those with which we were familiar, streets and factories were being lighted with discharge lamps. Success did not come without effort. Difficulties of colour rendering pressed upon us: lovers closed their eyes at their kerbside trysting places; workmen threw away their sandwiches and admonished their wives. But economics prevailed—assisted by the admixture of incandescent lamps and mildly effective fluorescent coatings.

Now we have the tubular fluorescent lamp. Its full possibilities have not yet been exploited, perhaps they are not even realised; nevertheless, fluorescent lamps have been applied—and well applied—to many different lighting tasks. We have high efficiency and good colour together, and we are learning how critical it is possible to be when a choice of colours is offered.

Looking back over the progress of lighting as an art and a science one cannot find any outbursts of enthusiasm or any technical advances comparable with those engendered by these new lamps. We ask, therefore, " What is the likelihood of further revolutions in lamp design? " The answer is less hopeful than it was twenty years ago. Then, new ways were opening up and their ends were far out of sight. Now we think we see ahead more clearly and the views are less spectacular.

Perhaps electroluminescence will yield what we seek. It is probably the only entirely new method of light production being studied at present; it has received much attention and publicity. Unless, however, we can make some remarkable additions to our knowledge it seems destined to remain primarily a laboratory novelty with little value for everyday lighting.

Even if an efficient lamp is produced it may not have the revitalising effect of some of its predecessors. Many remarkable sources—such as the compact source mercury discharge lamps, and the xenon and other rare gas arcs—give the impression that they should enable us to solve some knotty problems, but we have been able to make much less use of them than the ingenuity and skill of their designers deserve. However, research frequently finds itself on a plateau with no obvious new way up. Other sources will surely evolve although perhaps less frequently than in recent years. In the meantime we shall benefit from many detailed improvements such as new luminescent powders which increase efficiency and improve colour rendering, improved manufacturing techniques giving more reliable lamps with longer lives, and simpler and cheaper control circuits.

Research on Seeing

In many ways the most fascinating research in lighting is that which aims at understanding the behaviour of the visual mechanism.

The work follows two parallel channels. The one is concerned with the anatomy of the eye and attempts to determine its structure and method of operation; the other is directed to measuring visual performance such as acuity, threshold of brightness difference and spectral sensitivity.

Many famous men have experimented and theorised on the functioning of the eye without reaching an acceptable solution. Work by such investigators as Granit, at the present time, measuring electrical impulses in the nervous system of animal eyes, suggests that, however complicated we once thought eyes to be, the reality is more complicated still. Just as the modern atom has found itself unsatisfied with simple electrons and protons, and has taken on neutrons, mesons, neutrinos and the rest—so the modern eye demanding more than the structure of yesterday, proves to have an astonishing array of nervous cross-linkages whose purpose we can scarcely guess at. There is much mystery to unfold here, and the solution, if ever we reach it, should be exciting.

But generally, the lighting engineer will be more interested in the other channel

of research, namely the measurement of visual performance, since the results may help him to design lighting installations.

For example, if we know how the acuity of vision is related to brightness we should be able to specify the appropriate brightness—and hence, illumination—for different tasks. We should be able to study glare to the point of knowing how it may be limited to avoid discomfort, and to define brightness patterns which give "efficient" seeing.

I think, however, we should not hope for too much from such work as an influence on lighting design. We have been using our eyes for a long time and it seems unlikely that there are as yet undiscovered any unusually ingenious ways of exploiting the sense of sight for ordinary jobs. For special purposes—for example, lighting instrument panels when dark adaptation is to be retained—there are often cunning solutions based on little appreciated visual characteristics, but for the lighting of shops, factories and offices, the chief value of such work is to remove the "hit-or-miss" approach to design rather than to discover new methods of lighting. Its prime object is to enable us to put values to information previously specified in qualitative or, at best, crude quantitative terms. It may not lead directly to new lighting techniques, but it will help to raise the level of the average everyday installation by removing some of the guesswork in design.

Of course, that research on vision is not peculiar in tending to confirm what is already known rather than revealing new facts. This is true also of most other research. In the domain of physics as a whole, by far the greatest mass of experimental and, indeed, theoretical work is directed towards explaining known phenomena. Only rarely does an investigation yield an entirely new crop of knowledge. If this is true of physical science with vast regions as yet unexplored, how much more true is it likely to be of so well-tried a human organ as the eye.

In this respect the lighting engineer may perhaps compare himself with the psychologist whose studies lead to a considerable understanding of the working of the mind. He can analyse human behaviour: he can even offer plausible explanations of it. And often his conclusions will be those which would have been reached by a good judge of men without the analysis.

It seems unlikely that Solomon, when he gave his historic decision in the "Case of the Stolen Baby" considered consciously such matters as the primitive Id, or the super-normal Super-Ego; but he "got there" just the same. Even in Solomon's day men and women had been dealing for so long with men and women, that some of them knew well how to go about these dealings. But this was true only of a select few, and one of the tasks of psychology must be to help more of us to understand ourselves. Research on seeing aims also to teach more of us to understand ourselves.

The results of such research are only valid for the particular conditions of the experiment from which they were obtained. Almost invariably in research on seeing, these conditions are so restricted that one is tempted to extend the range of validity of the results. This is difficult and dangerous. For example, Lythgoe's work on visual acuity has been invoked to support the twin fetishes of uniform illumination and uniform brightness. This is unfortunate. What Lythgoe showed was that a very small test object near the limit of resolution of the eye would be seen better if it were brighter, and if it were surrounded by a field of slightly lower brightness. For convenience he used a surrounding field subtending a hemisphere—that is nearly the complete visual field—and as a result some people have assumed that a large, uniformly bright field is essential for good seeing. In fact, if Lythgoe had extended his work he would have shown that a surround subtending only 10-20 deg, at the eye was so nearly equal to a complete surround as to be almost indistinguishable from it.* Surely experience shows not only that large variations in brightness can be

* Work not yet published by C. A. Foxell and W. R. Stevens.

tolerated without harm but that these variations are attractive. Where deductions from experiment conflict with experience and commonsense they should be examined with care. Sometimes in our desire to discover some new and spectacular fact, we seem inclined to overlook this.

It seems to me therefore, that research on seeing is unlikely to shatter our present notions about lighting or to lead us to radically new methods. It can, however, put our ideas straight, make practice definite instead of vague, and so enable the average lighting engineer to do better work. Its value, therefore, is great.

The Study of Installation Design

Lighting is based upon two factors, light and the sense of sight, which still hold many unknowns. The nature of light, as far as it can be explained at all, can only be described by a mathematical physicist in language incomprehensible to most of us. The mechanism of seeing is the subject of beautiful experiment and heated argument. As in all other realms of knowledge we know much of what things will do and little of how they do it.

Lighting practice at the present time is still largely a matter of "cut-and-try." We have a few useful rules which help to guide us in designing an installation: we also have a few rules which seem to have no foundation in experiment or common sense. But for the most part we must design by experience. Sometimes, however, experience degenerates into routine and this we should avoid.

Various research groups in this country and others are paying increasing attention to practical aspects of lighting: they are trying to find sensible solutions to practical problems, and to interpret their more theoretical studies in practical ways. This work can be of great value, particularly if installation engineers will try to make it valuable. It is not always easy for the research man to know best how to present his information; the installation engineer can help by stating the form which he needs. The research man can seldom try his ideas in practical installations: it is the installation engineer who can put the ideas into effect.

But quite apart from contributions to installation design made from research groups, can we not do more in everyday jobs by a greater use of imagination? We have many tools to hand and a great store of knowledge. We should be asking ourselves always whether we are making the best use of them or whether we are following the stereotyped pattern of what was done yesterday and the day before. It is always easier to follow than to lead, and in the day-to-day routine of work the effort which can be put into each given job must be limited. Yet, in spite of this, every now and again one sees installations which express new ideas, and one feels sure that we are capable of designing more such installations and even better ones. Can we not try some of the more unorthodox suggestions which have been made from time to time—for example, artificial lighting which varies in colour and intensity with the changing seasons or weather, and windows intended to provide a view rather than to light the interior? Do we pay sufficient attention to reducing the cost of maintaining installations? Are we giving sufficient attention to the decorative element in lighting?

The last question is one which our Society has discussed frequently and on which we have had some noteworthy contributions. We all realise the importance of having in the industry men who combine artistic flair and engineering discipline. There is, no doubt, a limited number of methods of lighting: the fundamental laws of reflection and refraction are simple, well-known and unchangeable. The notes in our scale, as it were, are strictly defined. The problem is how to devise new tunes. The solution, in the decorative content of lighting practice at least, lies in ingenuity and variety, not forgetting the variety of fashion.

Many people tend to regard fashionable changes with some contempt, their

argument being, perhaps, that beauty should have permanence and good taste should not be ephemeral, an argument often strongly influenced by the fact that fashion in clothing, especially feminine clothing, appears to be determined by a few designers who are recognised leaders, rather than by a logical trend.

This dislike of fashion is unsound, for fashion provides variety and variety is even more than the "spice of life" or "the Mother of Enjoyment." Innate in all of us is the need for change and contrast in our daily lives. In all art forms, contrast is of vital importance for without it there is no art and life itself has no meaning. But this need for contrast does not only apply within a given work of art; it applies also in time, from one work to the next. Inevitably, therefore, over the years performances change, and popular fancy shifts from one composer to another, from one painter to another, from one playwright to another. And these changes in public favour are, of course, encouraged by the artists, composers and playwrights themselves, who are constantly seeking new methods of expression.

In those forms of self-expression such as architecture and lighting, which are closely allied to engineering, there is an additional impetus to change because of the advances in technology. The intensive study of material things which is the main occupation of our age results in a never-ending stream of new apparatus and new techniques permitting us to do to-day what we could not do yesterday, and this accentuates our desire to have to-day something different from yesterday.

Hence, change in fashion is an essential element of living and one not to be resisted but to be encouraged. We should be "making fashion" more often, rather than copying in a humdrum effort-saving way, what we have always done. This is difficult for there are limits beyond which one cannot experiment on one's clients, and clients are often even more "stick-in-the-mud" than we are. But the effort is surely worth making. We have the ideas: our great weakness often is in failing to try them on a large scale.

Public taste will often lead us round in a circle so that we appear to be back at our starting point. This seems very likely to happen in lighting because of the limited methods available, and if one looks through the literature it is interesting to observe how many lighting methods have come and gone, and come again. Indirect lighting, laylights, cornice lighting, graded window heights, have their vogue for a few years, recede in importance and then are revived—often with a flourish of trumpets which suggests that a great discovery has been made. We all like to think that we have done something for the first time. But even if we have not produced a new idea we may have improved on the old one, and in any event, the old idea will be new to the new generation.

This "coming full circle" or, more properly, using elements of older styles and applying them in a modern way, is common to all forms of art. In interior decoration there is a revival of interest in "Victoriana" with patterned wallpapers and embellishments coming again into favour. In the theatre, people are actually paying to hear plays written in verse. And in England a few men are reverting to coloured waistcoats and beards. These are all reasonable and good trends, as long as they are not merely unconstructive and slavish imitations of the past.

As in decorative lighting, so in all other branches of lighting, the application engineer must continue to find better ways of doing his job. If he is to receive less stimulus than in the past from new light sources, he must seek to provide the stimulus in other ways. He must improve his own standards.

Education and the Society

I have said already that the task of the lighting engineer is made difficult by the few notes on his scale. He is faced with another difficulty which we do not

* Disraeli (Vivian Grey, Book V).

always recognise, and that is that generally the bulk of his job is done when some light is provided, whatever that light is. A man lost in a cave will pray for light. If he gets it and his life is saved he is unlikely to complain that the colour is bad, that the efficiency is low or the brightness pattern of the surroundings is poor.

It is only when one's tastes become more subtle that the bare minimum becomes insufficient and that the luxury of yesterday becomes the necessity of to-day. It is then that clothes must adorn as well as protect, food must be pleasant as well as nourishing, lighting must look good as well as enabling us to see. But most of us are content with what we have until we are shown that we could have something better. "What you've never had you never miss" is the old saying. So it is that many people have inefficient, unattractive, and often archaic lighting and we must try to show them how much better it could be done. This will be difficult because the bare provision of light is so simple that nearly everyone regards himself as a lighting expert and cannot understand how anyone else needs to devote a lifetime to the subject to be proficient in it.

If we are to advance it is essential that the user as well as the designer appreciates what is "good" lighting. In our Memorandum of Association we read that the first object for which this Society is established is "To promote the general advancement of illuminating engineering and the utilisation of natural and artificial light and the dissemination of knowledge relating thereto."

How is the Society to educate the user? It can, as it already does, provide literature and lectures for those who will make use of them. But for several reasons it is doubtful whether this is the Society's most powerful weapon. Firstly, unless this type of propaganda is done very skilfully, it smacks strongly of commercialisation. Now the commercial element is essential and desirable provided it is confined to commerce. The Illuminating Engineering Society is not a commercial platform, nor would the lighting industry wish the Society to be of direct commercial value. Indeed, this is a good point at which to pay tribute to the many firms who contribute large sums of money directly and indirectly to us expecting a return only in so far as the status of the lighting industry is raised by our efforts. The Society could not exist without this help, nor could it exist if the help were subject to conditions.

The second difficulty reducing the effectiveness of written propaganda is that we are all subject to so much of it nowadays. Advertisements, books, catalogues, all tell us how much better life would be if we did this, that or another. Improve the heating in our home by changing the grate; improve the peoples' larder by growing pigs; improve the national economy by saving. An avalanche of advice descends upon us: we are overwhelmed and pay no heed.

This shows us the third and most serious difficulty: you cannot instruct those who will not be instructed. It is a maxim that you cannot teach a child—you can only expose him to information. And not always will the exposure secure the desired result.

Surely, the best course is to expose the user to good lighting rather than good verbiage. By all means let us educate with all the weapons we have, but let us ensure that the surroundings in which we move exemplify the things we praise. And this brings us back to the most important single duty of the Society, namely to help us to educate ourselves.

The advances in a subject are made by the few but the standing of a subject is judged by the ability of the general practitioners. It is of little value that the Festival Hall is well lighted if the many other public buildings up and down the country are not. Do all the new lighting schemes give good results at a reasonable cost? If the answer is "no" it may be because a lighting engineer has not been given the job. But could we do the job given the opportunity? We often inveigh against the architect, saying "If only you consult your lighting man early you will get a good installation." But supposing one were given a blank sheet by the architect; supposing

one were told " I have to build a restaurant, a church, or a theatre; if you prescribe the lighting I will fit my structure around it "; how many of us could achieve a result above the average ?

If we are to improve the general standard of lighting we must endeavour to do each job a little better than the last one. Some of this improvement will come from within each of us, from a study of the mistakes we have made, of the " things that could have been better ": but much more will come by comparing our efforts with those of others, by discussing and interchanging ideas. Here is the Illuminating Engineering Society's main task and opportunity. By providing a platform from which we can air our views, a journal in which those views can be recorded, meeting places in which we can compare notes informally as well as formally, the Society plays a vital part in improving standards of lighting. Any other tasks we perform as a Society are secondary to this one of improving the abilities of its members; that is, of helping us to help each other.

For we must remember that *we* are the Society; its success and its value come from what we, its members, put into it, and the more we put in the more there is to take out. In particular an even bigger part should be played by the application engineers, the bulk of the members, the people whose job it is to install lighting. I would like to see more of them at our meetings, particularly our summer meeting, where the opportunity for discussion and intermingling is greatest; I would like them to make more contributions to our Transactions, not simply by describing particular lighting installations, but by discussion of the problems involved and the solutions found.

The research side of the industry has already made great contributions to the subject and will continue to do so: but lighting more than many other matters in this age of committees, depends vitally upon the commonsense and experience of the individual designer, and the Society must have his support.

The Society needs, too, to broaden its membership, for lighting is so essentially a personal and living study that we must avoid becoming a small, self-contained clique trying always to feed on our own ideas. We need the stimulus of contact with artists, ophthalmologists, architects, and all those others concerned with lighting and vision, but not wholly occupied with it. Our retiring President has wisely pointed out this need to interest those whose work is on the fringe of lighting as we know it.

During the few years of its existence the Society has achieved much. It has played a considerable part in setting standards of good lighting, and in showing how they may be achieved; it has encouraged the training of recruits to the industry and has helped to set up the City and Guilds Examinations for which there have been 601 entries in the last five years; it has made its contribution to national and international deliberations—its members serve on over 50 Government, British Standards and other Committees, and 55 delegates went to the last C.I.E. meeting in Stockholm : it has gained recognition as an impartial authority. Above all, it has assisted an increasingly large membership to do increasingly good work. This is worth doing and worth doing better; for man has few blessings greater than that of sight, and the Society is trying to multiply that blessing. It is with pride, therefore, that we claim as our object "TO SPREAD LIGHT EVERYWHERE."

Spectrophotometry of Radiation from Sun and Sky

By E. R. COOPER, Ph.D., M.Sc., and M. C. PROBINE, M.Sc.

Summary

A spectrophotometer is described by means of which the spectral distribution of radiation from the sun and sky, or the sky alone, may be conveniently measured if the sky is either completely clear or completely overcast. The instrument is calibrated using a standard lamp, whose spectral energy distribution is known in the region 0.4 micron to 0.7 micron. A "fatigue-correcting" lamp, included in the optical system, enables the results to be expressed in energy units. Possible errors are discussed.

(1) Introduction

The spectral distribution of solar radiation has been the subject of many investigations, the most notable being those of the Smithsonian Institution. At the earth's surface it varies from day to day and from season to season, according to the sun's altitude and the water-vapour, dust, and ozone contents of the atmosphere. Moon([1]) has compared the data obtained by various investigators on the spectral distribution of solar radiation outside the earth's atmosphere. On this basis he has recommended a "proposed standard curve" from which, by making assumptions about atmospheric transmission, the spectral distribution for any part of the earth's surface at any time and any elevation above sea level can be computed. Other investigators have adopted other spectral distributions as being satisfactory approximations to that of sunlight, e.g., biologists have sometimes used that of midsummer noon sunlight at Washington, D.C.

So far the only spectral distribution considered has been that of direct solar radiation, but for many purposes (e.g., some problems in illuminating engineering, study of plant growth in controlled environment, photographic sensitometry, natural colour photography) it may be more useful to know the spectral distribution of daylight, which includes radiation from the whole of the sky as well as direct solar radiation. Further, the effects of clouds should be taken into account. Unfortunately, very few measurements of the spectral distribution of daylight have been made, and "the few available data at present do not permit a satisfactory definition of 'normal daylight' in the meaning, 'normal sunlight' plus 'normal skylight' is 'normal proportion'"([2]). In this paper a spectrophotometer is described which measures the spectral distribution of radiation from the sun and sky falling on a horizontal surface. Fig. 1 shows a general view of the instrument.

(2) The Integrating Device

If the spectral distribution of radiation from the sun and the whole sky is to be measured, it is necessary to specify the shape and direction of the surface on which the radiation falls. In this paper, only a horizontal plane surface is considered. Other surfaces which could be considered for future work are vertical plane surfaces facing north, south, east, or west.

An unmodified spectrometer cannot be used for this measurement as the angle of view of the optical system is small, so that if the collimator was pointed vertically upwards only radiation from the zenith would be received. However, by using a simple integrating device which fits over the collimator, it is possible to arrange for

The late Dr. Cooper was, and Mr. Probine is, at the Dominion Physical Laboratory, Department of Scientific and Industrial Research, New Zealand. The manuscript of this paper was received on October 5, 1953.

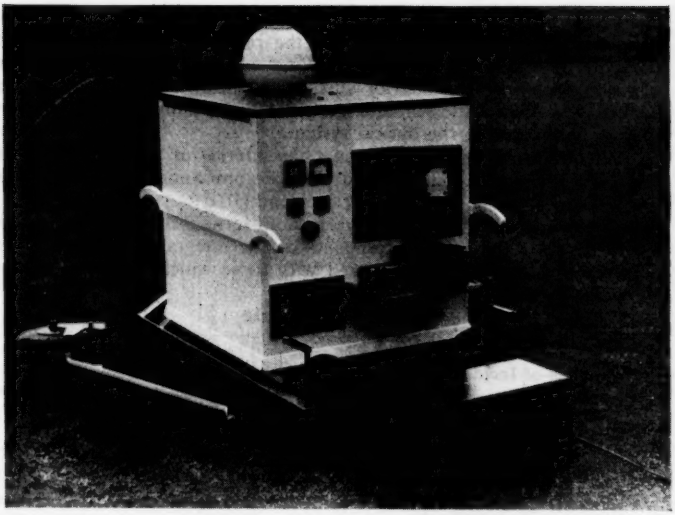

Fig. 1. D.P.L. Spectrophotometer.

the radiation entering the spectrometer to have the same spectral distribution as that falling on a horizontal surface[3].

The integrating device (Fig. 2) consists of a hollow sphere coated inside with magnesium oxide. Radiation entering the sphere by an annular opening at the top is diffusely reflected by the interior surface, which is therefore uniformly illuminated in proportion to the radiation falling on a horizontal surface (i.e., entering through the annular opening). At the centre of the annular opening there is a disc which forms

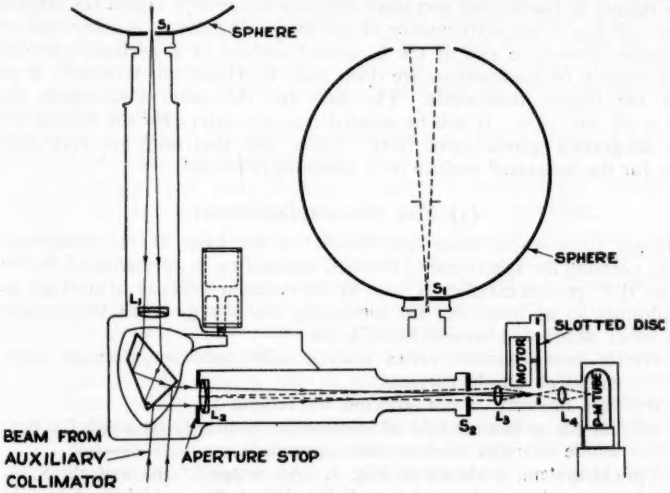

Fig. 2. Integrating device and optical system of D.P.L. Spectrophotometer.

part of the interior surface, and is the only part of it which is viewed by the spectrometer. The spectral distribution of the radiation entering the spectrometer is thus the same as that of the radiation falling on a horizontal surface, provided that the reflection factor of the interior surface is uniform throughout the spectrum. The diaphragm between the slit and the annular opening is designed to reduce the risk of stray light entering the optical system.

Magnesium oxide is used to coat the interior of the sphere because :—

(a) a magnesum-oxide coated surface approximates closely to a uniform diffuser, except for large angles of incidence[4].

(b) its reflection factor is high and uniform throughout the visible spectrum[5].

In Table 1 the relative responses of the integrating device for various angles of incidence of radiation are compared with those which would be obtained if the cosine law were obeyed.

Table 1

Angle of Incidence	Relative Response (±0.02)	Cos θ	Relative Response corrected for wall thickness* (±0.02)
(deg.)			
0	1.00	1.00	1.00
15	0.96	0.97	0.96
30	0.85	0.87	0.85
45	0.68	0.71	0.68
60	0.47	0.50	0.47
75	0.22	0.26	0.27
80	0.13	0.17	0.17
85	0.04	0.09	0.07
90	0.00	0.00	0.00

* The effective area of the annular opening, at angles of incidence approaching 90 deg., depends on the thicknesses of the disc and the wall of the sphere.

The figures in the second and third columns agree well except for large angles of incidence. In Fig. 3 the performance of the integrating device is compared with those of an Eppley thermopile and of the lacquered surface of a selenium photocell. The scale and method of presentation are those used by Hand and Woertz[6] in presenting data for the Eppley thermopile. The data for the other instruments have been adjusted to fit this scale. It will be noticed that the curves for the Eppley thermopile and the integrating sphere agree fairly closely, and that both are very much better than that for the lacquered surface of a selenium photocell.

(3) The Spectrophotometer

A Hilger constant-deviation spectrometer is the basis of the equipment. Since the energy entering the spectrometer is much reduced by the presence of the integrating sphere, an IP22 photomultiplier is used as the detector because of its high sensitivity.

In addition to its suitability for measuring low energy levels the photomultiplier tube has other desirable characteristics[7], viz.:—

(a) Its anode current varies linearly with radiation intensity over a large range of anode currents.

(b) This linearity is not affected by fatigue.

(c) Fatigue is independent of wavelength, and is fairly small for the range of anode currents used in this equipment.

The optical system is shown in Fig. 2. An image of the exit slit S_2 is focused by a lens L_3 on to the surface of a radially slotted disc, which is driven by a syn-

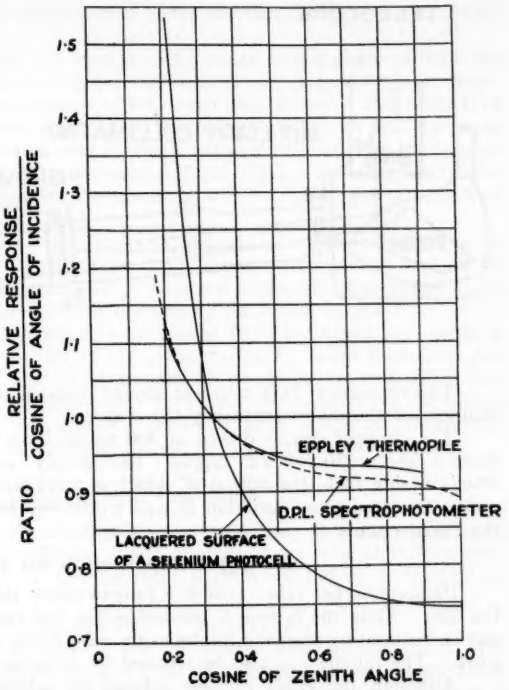

Fig. 3. Performance of integrating device of the D.P.L. Spectrophotometer compared with the performance of an Eppley Thermopile and a selenium photocell with a lacquered surface.

chronous motor. This rotating shutter interrupts the radiation incident on the cathode of the phototube 233⅓ times per second, and the pulsating direct-current output is amplified by a tuned linear a.c. amplifier. The output is indicated on a 0-360μA meter. A simple variable attenuator in the input gives a range of sensitivity from 200 : 1 in seven steps; this method has the advantage of allowing the amplifier to operate with fixed gain.

The chopping method, by which uninterrupted radiation produces an alternating signal, was adopted for the following reasons:—

(a) It would have been difficult to design a portable d.c. amplifier having a stability comparable with that of an a.c. amplifier.

(b) Even when no radiation is falling on the cathode, there is a residual "dark current" which varies with time, dynode voltage, and, under some circumstances, humidity. By interrupting the radiation and amplifying the d.c. pulses, this undesirable dark current, being a d.c. component of the resulting signal, is not present in the output.

(c) By chopping the radiation at a definite frequency, it is possible to use an amplifier having only a narrow bandwidth. This is advantageous, since only a narrow band of frequencies, from the whole spectrum of noise associated with signals from a photo-multiplier, is allowed to pass through the amplifier and reach the output. Thus the signal-to-noise ratio is less than with d.c. measurement of the signal from a photo-multiplier.

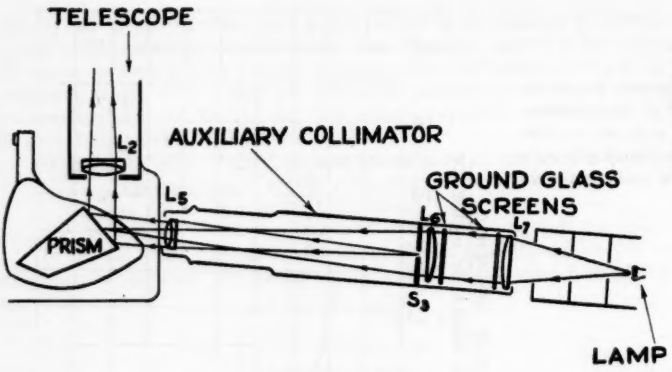

Fig. 4. Auxiliary collimating system of D.P.L. Spectrophotometer for fatigue compensation.

The frequency 233⅓ c/s was chosen because it was convenient and was not a multiple of the mains frequency (50 c/s).

The chopper disc is driven at 400 r.p.m. by a Venner motor, which is operated from a 50-c/s 230-volt a.c. supply. This supply is obtained from a valve-maintained 50-c/s tuning fork, the output of which is amplified by 6V6 valves working in push-pull. The frequency variation is well within the limits set by the high selectivity of the tuned circuit.

(4) Compensation for Fatigue

Photomultiplier tubes exhibit a fatigue effect, the magnitude of which varies with the tube. Since the fatigue is greatest in the first few minutes after starting, the effect can be reduced by allowing the tubes to settle down for some time before commencing work. The fatigue can also be reduced by working with small radiation intensities.

Although the effect can be reduced by selecting the tube and using it under favourable conditions, it is still necessary to allow for fatigue if the equipment is to retain its calibration in energy units when there are comparatively long intervals between successive runs through the spectrum. The method of allowing for fatigue is shown in Fig. 4.

A parallel beam of radiation from an auxiliary collimator is directed at the prism face at such an angle that when the wavelength drum is set on 0.395 micron the beam is reflected from the prism face through L_2, S_2, L_3, and L_4 on to the photocathode. A small six-volt 12-watt lamp, operated on constant current, is used as a source of constant radiation. At the end of each run through the spectrum from 0.7 micron to 0.42 micron, the radiation beam through the main collimator is cut off and the output from the lamp is measured. The indicated value is a measure of the instrument sensitivity, and allowance can be made for fatigue. While the daylight spectrum is being measured, radiation from the lamp is cut off.

The sensitivity of the photomultiplier tube is far from uniform over the cathode. Dieke[7] has reported that a small spot of light focused on to the cathode and moved across it in a horizontal direction shows considerable differences in sensitivity in different parts of the cathode. When the spot is moved vertically, sharp periodic fluctuations are found, due to the horizontal wires of the protecting grid in front of the cathode. Dieke also investigated the effect on the observed fatigue of varying the size of the image. He says: "This experiment was carried out, using one time a very narrow and another time a very broad slit. The intensities were adjusted so as to result in the same photo-current. No significant difference in fatigue was observed. This, however, was different when the length of the slit was changed. A short slit

intensely illuminated will show more fatigue than a long one illuminated correspondingly less."

From the above considerations, it is clear that the image on the photo-cathode due to the fatigue-correcting lamp described above should be similar in position, size, shape, and uniformity to that due to the presence of the integrating sphere. The integrating sphere acts towards the spectrometer as a diffuse source, with the result that the image on the cathode is uniformly illuminated over its whole area. Radiation from the fatigue-correcting lamp must therefore also be rendered diffuse. This is done by interposing two lightly-ground glass screens between the lenses L_6 and L_7. The screens are about 2-in. apart.

Immediately in front of the lens L_2, there is a rectangular aperture stop arranged to define the sizes of both the refracted beam from the main collimator and of the reflected beam from the auxiliary collimator. It is the uniformly illuminated image of this aperture stop which is focused on the cathode by the lenses L_3 and L_4.

There is a second, indirect advantage to be gained from the above arrangement. As previously mentioned, the sensitivity of the photomultiplier varies from one part of its cathode to another, and if the extremely narrow image of the exit slit S_2 was focused on to the cathode, a small displacement of the tube relative to the optical axis would alter the calibration. Focusing a relatively large image of the aperture stop on the cathode reduces the risk of tube movement causing a serious error.

(5) Calibration and Operation

The sensitivity of the IP 22 photomultiplier is a maximum at about 0.42 micron and decreases with increase of wavelength, being approximately zero at 0.80 micron. Further, the spectral distribution of the radiation is modified before it reaches the cathode by :—

(a) selective absorption by the glass of the optical system,

(b) variation of the dispersion of the instrument with wavelength. (The unilateral entrance slit is set at a fixed width during a run and the band-width (to half peak) varies between 0.003 micron at wavelength 0.42 micron, and 0.025 micron at 0.70 micron),

(c) the slight variation of the reflection factor of magnesium oxide with wavelength.

In order to measure the sensitivity of the spectrophotometer at each wavelength, a tungsten lamp of known spectral distribution is used as a reference source. By multiplying each reading by the factor appropriate to the wavelength, the readings may be expressed in microwatts per square centimetre per 0.1 micron. The sensitivity, as indicated by the fatigue-correcting lamp, is checked before and after each run to ascertain whether it has changed sufficiently to affect the reading appreciably, and if it has, a small correction is made to each reading. On most days wavelength errors checked with a sodium lamp have been insignificant. The accuracy of wavelength setting is approximately 0.001 micron.

The measurement of the spectral distribution from 0.42 micron to 0.7 micron takes about four or five minutes. It is therefore necessary to work only when the radiation intensity is constant throughout the run, otherwise it is impossible to separate changes in output due to changes in radiation intensity from those due to changes in spectral distribution.

This ideal is realised when the sky is perfectly clear and when the sun is at high or medium altitudes (i.e., the air mass and the cosine of the zenith angle are not changing rapidly). When the sky is completely overcast, changes in radiation intensity are very slow and may be followed with a photometer, so that a correction can be made to the output reading at each wavelength.

When clouds are moving near the sun, reflections cause very large random

fluctuations in radiation intensity, for which corrections cannot be made conveniently or accurately.

(6) Effect of Changes in the Reflection Factor

It can be shown that the intensity of radiation at the slit is proportional to

$$\frac{\rho^2}{1-\rho\,(1-b)}$$

where ρ is the reflection factor of the sphere surface, and
b is a constant depending on the dimensions of the sphere and annular opening.

The factor (1—b) is a correction term to allow for the loss through the annular opening of some of the radiation reflected within the sphere.

If the reflection factor of the coating is very high, a small change in the reflection factor will cause a large change in the energy reaching the slit. Measurements were therefore made to determine the order of the changes in sensitivity from this cause. The 500-watt tungsten-filament projector lamp of known spectral distribution was used as a constant-energy reference source, and the indications of the spectrophotometer output meter, for each of eight wavelengths, were observed over a 20-day period starting with a freshly coated sphere surface. After a correction had been made for

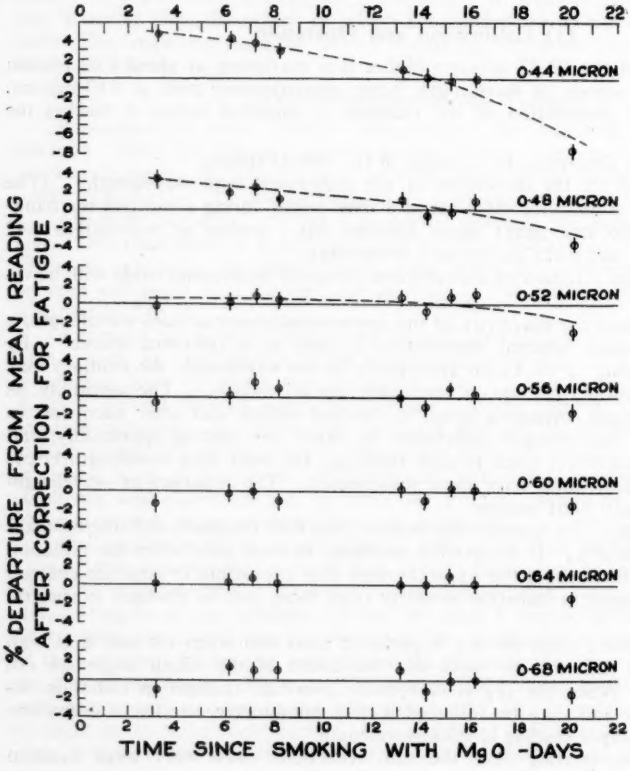

Fig. 5. Effect of change in reflection factor of integrator coating with time for a number of wavelengths.

fatigue of the photomultiplier, the percentage departure from the mean output for each wavelength was plotted against time. The lamp source was switched off between readings.

The results are shown in Fig. 5. There appears to be negligible change in sensitivity (within the limits of accuracy) for wavelengths between 0.52 micron and 0.68 micron. From 0.52 micron to 0.44 micron the sensitivity appears to decrease, the effect being more marked as the wavelength decreases. This is consistent with earlier work[8] which showed that the spectral reflection factor of a magnesium-oxide surface may change perceptibly within a short time after preparation, and that the nature and extent of the changes are variable and are greatest below 0.55 micron. The need for fairly frequent calibration is apparent.

Acknowledgments

We should like to thank all those who offered help and advice; particularly Messrs. M. H. Hall, J. N. Hull, H. W. Robertson, and N. J. Rumsey. The amplifier and electronic equipment were designed by Mr. J. Templeton[9].

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Appendix

Error in the Measurement of the Spectral Energy Distribution due to Departure of the Integrating Sphere from the Cosine Law

In these measurements it is assumed that the spectrometer receives radiation which has the same spectral distribution as that falling on a horizontal surface, i.e., that the integration device obeys the cosine law. It has been shown (Table 1) that, although this is approximately true, there are significant departures from the cosine law at large zenith angles. These departures will cause an error in the calculated colour temperature.

Middleton ([10]) described a method of comparing the behaviour of pyrheliometers used to measure radiation falling on a horizontal surface. His treatment was developed to meet a requirement slightly different from that considered here, but it can be used to give a rough estimate of the error in the spectral distribution caused by departure from the cosine law. The treatment which follows is a summary of that given by Middleton, with modifications to suit the present discussion.

The brightness of a portion of the sky may be expressed as a function of its zenith angle θ, azimuth ϕ, and the time t. If we assume the brightness does not vary with azimuth (which is justified if the receiver is symmetrical), then for any given instant it can be shown that the energy per unit area per unit time from the whole sky, falling on a horizontal surface, is given by

$$I_1 = \int_0^{\pi/2} 2\pi \sin\theta . \quad f_1(\theta) . \quad \cos\theta \, d\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where $f_1(\theta)$ takes into account variations in the brightness of the sky with zenith angle.

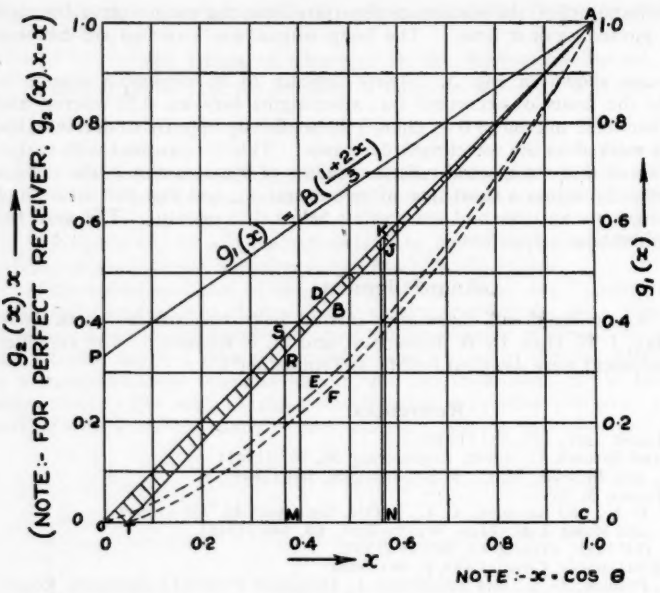

Fig. 6. Relation between $g_2(x).x$ and x for perfect receiver and the actual integrating sphere.

Owing to departure from the cosine law, the fraction of the energy entering the sphere by the annular opening is a function of the zenith angle.

Let this function be $f_2(\theta)$.

$$\text{Then } I_2 = \int_0^{\pi/2} 2\pi \sin\theta.\ f_1\theta.\ f_2(\theta).\ \cos\theta.\ d\theta \quad \text{.....(2)}$$

Substituting x for $\cos\theta$, and writing $f_1(\theta) = g_1(x)$
$f_2(\theta) = g_2(x)$

$$I_1 = \int_0^1 2\pi.g_1(x).\ x.\ dx. \quad \text{.....(3)}$$

$$I_2 = \int_0^1 2\pi.g_1(x).\ g_2(x).\ x.\ dx. \quad \text{.....(4)}$$

The function $g_2(x).\ x$ can be obtained from the figures given in Table 1, column 2, and in Fig. 6 it is shown plotted against x (curve TBA).

The energy received on a surface which obeys the cosine law varies as $\cos\theta$, that is to say, x. The straight line ODA in Fig. 6 represents $\cos\theta$ plotted against x.

Referring to equations (3) and (4), let I_2/I_1 be called the efficiency for a given distribution $g_1(x)$ and let this efficiency be calculated for a number of wavelengths throughout the spectrum, for various zenith angles of the sun.

(I) Overcast Sky

Suppose the sky is completely obscured by clouds. The brightness B of the sky may be taken to follow the law [11].

$$g_1(x) = B\left(\frac{1+2x}{3}\right)$$

The equation represents a sky 33 per cent. as bright at the horizon as at the zenith. From equation (3) we have

$$I_1 = \int_0^1 2\pi.B\left(\frac{1+2x}{3}\right).\ x.\ dx. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Differentiating,

$$dI_1 = \left[\ 2\pi.B\left(\frac{1+2x}{3}\right)\right]\ \left[\ x.\ dx\ \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Similarly from (4):—

$$dI_2 = \left[\ 2\pi.B\left(\frac{1+2x}{3}\right)\right]\ \left[\ g_2(x).\ x.\ dx\ \right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

The above grouping of the factors within the square brackets points the way to a graphical procedure. The second bracket in (6) corresponds to an element of area of width dx, such as KN in Fig. 6, and the second bracket in (7) corresponds to JN. If now we plot the function $B\left(\frac{1+2x}{3}\right)$ against x as a line PA, and multiply the corresponding ordinates of PA and of ODA, we shall obtain a new curve OEA whose ordinates will be $B\left(\frac{1+2x}{3}\right)$ $.x$. Similarly from TBA we obtain TFA, the ordinates of which will be $B\left(\frac{1+2x}{3}\right)$ $g_2(x).\ x$.

The energy per unit area per unit time absorbed on an ideal surface from the whole sky is the integral from $x = 0$ to $x = 1$ of the right-hand side of the equation (6). From the way OEA has been constructed, it is evident that the area under this curve is represented by this integral. Similarly, the area under TFA represents that absorbed by the integrating sphere.

For this brightness distribution $\frac{I_2}{I_1} = \frac{\text{area } TFACT}{\text{area } OEACO}$ .....(8)

Fig. 6 summarises the results for the integrating sphere, and from this ratio $\frac{I_2}{I_1}$ has been calculated for the brightness distribution $B\left(\frac{1+2x}{3}\right)$.

In this case, $\frac{I_2}{I_1} = 0.93$.

(II) Clear Sky

Consider now a cloudless sky supplying α per cent. of the illumination, and the sun at a zenith angle θ supplying β per cent.

For these conditions the brightness distribution $B\left(\frac{1+2x}{3}\right)$ no longer holds. The spectral distribution and brightness vary over the sky, and it is difficult to see just what brightness distribution is likely to give the best approximation. A point in the sky lying in a vertical plane through the sun and 90 deg. from the latter is least bright. Nearer the sun (and the horizon) the brightness increases. Since the purpose of the calculations is only to estimate the order of the errors introduced by the integrating device, it has been assumed as an approximation that the sky is uniformly bright. The effect of departures from this condition will be discussed later.

For the component from the sky we apply the process described in (I) above. As all the radiation coming directly to the instrument from the sun is from the same

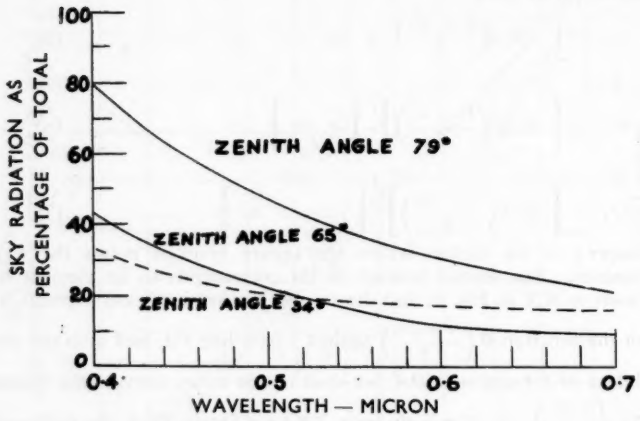

Fig. 7. Relation between sky radiation as percentage of total radiation and wavelength. (Clear sky—not all on same day).

part of the sky, the ratio of the ordinates MR and MS in Fig. 6 will give the ratio I_2/I_1 for the sun alone. The percentage efficiency under such conditions is therefore given by

$$100\,\frac{I_2}{I_1} = \alpha\left(\frac{\text{area } TBACT}{\text{area } ODACO}\right) + \beta\left(\frac{MR}{MS}\right) \qquad \text{.....(9)}$$

Apart from an obvious error in the measured energy, owing to the efficiency not being 100 per cent., there is a possibility of error in the relative spectral distribution. For any given zenith angle, the terms within the brackets will be constant; but the ratio of sky to sun radiation intensity will vary with wavelength (Fig. 7), i.e., the ratio α/β will vary throughout the spectrum. Hence the efficiency $\frac{I_2}{I_1}$ will vary with wavelength, and there will be a modification of the spectral distribution.

This error may be serious at large zenith angles, where

(a) at shorter wavelengths the clear sky supplies a larger fraction of the total radiation density than does the sun;

(b) the fraction supplied by the sky rapidly decreases towards the red;

(c) the ratio $\left(\frac{MR}{MS}\right)$ is appreciably different from the ratio $\left(\frac{\text{area } TBACT}{\text{area } ODACO}\right)$.

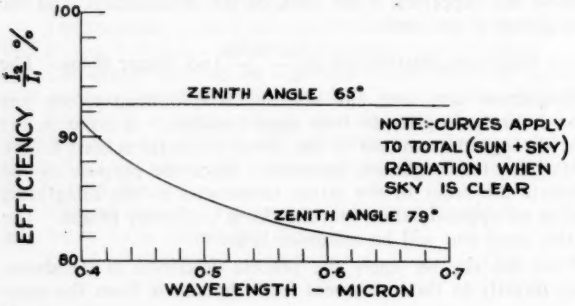

Fig. 8. Relation between efficiency of integrating sphere and wavelengths for different zenith angles.

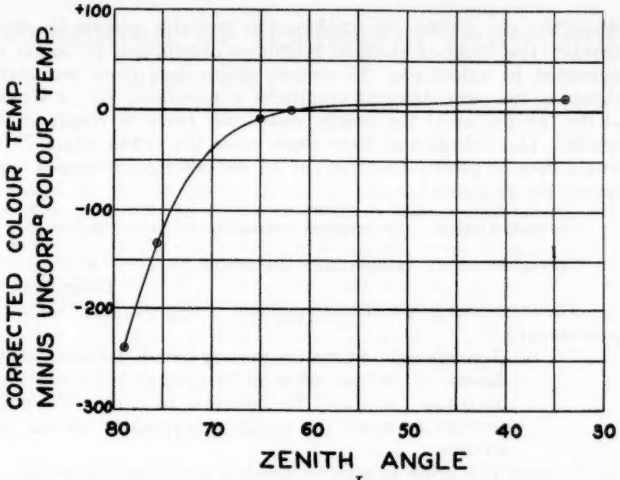

Fig. 9. Relation between error in colour temperature and zenith angles.

Using the data in Fig. 6 and Fig. 7, the efficiency $\frac{I_2}{I_1}$ has been calculated from equation (9), for each wavelength, and for a number of zenith angles of the sun. Examples of the way in which the efficiency varies with wavelength are shown in Fig. 8 for zenith angles 65 deg. and 79 deg. (on different days). At zenith angle 79 deg. the efficiency of the integrating sphere is approximately 10 per cent. greater at 0.4 micron than at 0.7 micron; whereas at zenith angle 65 deg. it is only 0.1 per cent. greater.

The effect of this efficiency change on the apparent colour temperature has been estimated by correcting the total (sun plus sky) radiation intensity value at each wavelength, to the value it would have had if the efficiency had been 100 per cent., and by calculating the colour temperature for the corrected and uncorrected spectral distributions. The results are given in Table 2 and shown in Fig. 9.

Table 2

Date	Zenith Angle of Sun	Air Mass	Colour Temperature		Difference	Remarks
			from corrected spectral distribution	from uncorrected spectral distribution		
(1)	(2)	(3)	(4)	(5)	(4)–(5)	
	deg.		deg. K.	deg. K.	deg. K.	
22/6/51	79.4	5.25	5,410	5,650	—240	No cloud, but very hazy
1/2/51	76	4.2	5,580	5,710	—130	No cloud
22/6/51	64.7	2.33	5,490	5,500	— 10	No cloud, slight haze
21/2/51	34	1.21	5,760	5,740	+ 20	$\frac{1}{8}$ cloud overhead

In the above calculations the brightness of the sky has been assumed uniform.

When the sun is low, the brightness is probably greater at the horizon than at the zenith. The effect of assumed brightness distribution on colour temperature has been estimated by calculating the colour temperature from the corrected energy values, assuming two very different brightness distributions, viz., a sky 33 per cent. as bright at the horizon as at the zenith; and a sky twice as bright at the horizon as at the zenith. The calculations have been made for zenith angle 79 deg., since the effect would then be greater than for any of the other zenith angles considered above. The results are as follows:—

Corrected colour temperature assuming $g_1(x) = B\left(\frac{1+2x}{3}\right) =$ 5,420 deg. K.

Corrected colour temperature assuming $g_1(x) = B(2-x) =$ 5,390 deg. K.

Difference = 30 deg. K.

The treatment given in this appendix is approximate, but it leads to the following conclusions:—

(a) The efficiency of the integrating sphere decreases as the altitude of the sun decreases, and the error in the energy scale will increase as the altitude decreases. It might be desirable to correct the energy scale by a fixed amount to make the results more nearly correct for high and medium altitudes.

(b) The error in relative spectral distribution does not appear to be serious for zenith angles greater than 75 deg., since differences in the spectral distributions of runs on the same day, or on different days at the same air mass, may give colour temperatures differing by 100 deg. K. or more. However, it is a systematic error, and at zenith angles greater than 75 deg it may be advisable to apply some correction to the results.

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Spectral Distribution of Radiation from Sun and Sky

By J. N. HULL, B.Sc.(Eng.), *(Fellow)*.

Summary

Measurements of the spectral distribution of the radiation falling on a horizontal plane from sun and sky have been made in various kinds of weather, using the transportable spectrophotometer described by Cooper and Probine. On overcast days the relative-energy/wavelength curve of sun and sky together is nearly the same as on clear days, although the amount of radiation is only about one-fifth. Haze, thin cloud, and mist produce more noticeable changes in distribution. On clear days small amounts of cloud cause large changes in the distribution of radiation from the sky alone. As an example of a simpler method of stating the distribution, which may be suitable where relative-energy/wavelength curves are unnecessarily detailed, the C.I.E. chromaticity co-ordinates and colour temperatures have been calculated for a few days.

(1) Introduction

The transportable spectrophotometer described by Cooper and Probine has been used at the Dominion Physical Laboratory near Wellington, New Zealand, in various kinds of weather and at different seasons. This paper describes the results obtained. Rain falls in Wellington during less than 10 per cent of the daytime, so that the inability to operate during rain has not introduced serious gaps in the observations.

The results are expressed in two ways, as relative-energy/wavelength curves and as colour temperatures. For ease of comparison the relative-energy scale is chosen so that the sum of the ordinates of each curve, read at 0.01 micron intervals from 0.42 to 0.70 micron, is unity.

(2) Types of Spectral Distribution

Most of the observations were made on the radiation from sun and sky together, but some were made on the sky radiation alone by shading the receiving surface from the direct rays of the sun. Nearly all the sun-plus-sky curves show a certain similarity in detail, for example they all have a peak at about 0.47 micron. This was examined in later tests where readings were taken at intervals of 0.01 micron. In every curve this peak was found to be double. In a similar way, more closely-spaced wavelength readings around 0.43 and 0.52 micron revealed dips in the curve similar to those reported by Taylor and Kerr [1]. The bandwidth of the spectrometer is, however, too great to permit detailed investigation of the spectral distribution. To cover the wavelength band as quickly as possible, readings were usually taken at intervals of 0.02 micron.

Tests made between 0900 and 1600 hours N.Z.S.T. have been grouped according

Table 1

Zenith Angles of the Sun

	0900 hrs.	1200 hrs.	1600 hrs.
Midsummer (22 Dec., 1951)	45 deg.	18 deg.	49 deg.
Midwinter (22 June, 1951)	80 deg.	65 deg.	82 deg.

The author is at the Dominion Physical Laboratory, Department of Scientific and Industrial Research, New Zealand. The manuscript of this paper was received on October 5, 1953.

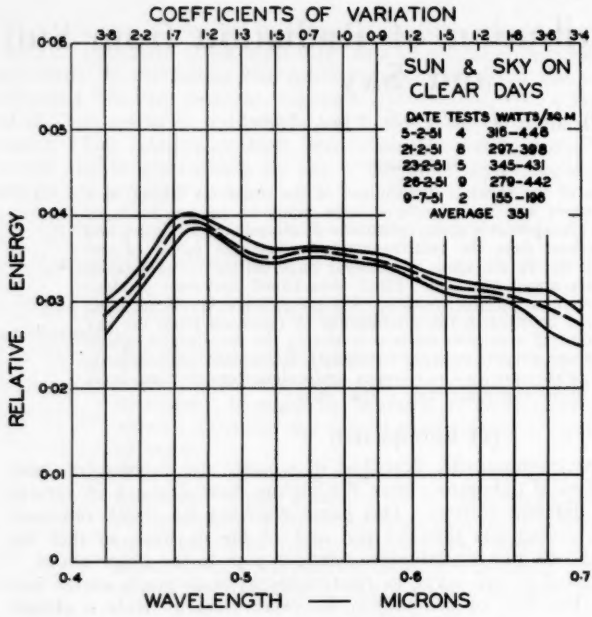

Fig. 1. Spectral energy distribution from sun and sky on clear days.

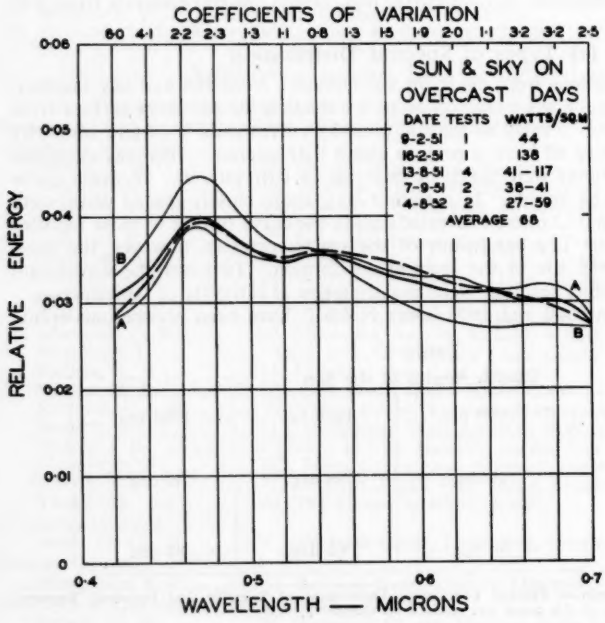

Fig. 2. Spectral energy distribution from sun and sky on overcast days.

to the kind of cloud cover. The zenith angles of the sun in summer and winter corresponding to these times are shown in Table 1.

(2.1) Clear and Overcast Days

In Fig. 1 the broken curve shows the average of 28 tests made on five days described as clear, i.e. with cloud cover of one-eighth or less. This curve is also repeated in later figures for comparison. The full curves indicate the limits within which all the readings fell, and coefficients of variation for the various wavelengths are given at the top of Fig. 1. Densities of radiant power between 0.42 and 0.70 micron are shown in the column headed "watts/sq.m," the two figures for each day being the maximum and minimum figures for that day. The average density for all 28 tests is also shown.

In Fig. 2 the thick full curve shows the average of 10 tests made on days with cloud cover of more than seven-eighths, and the broken curve is the average curve repeated from Fig. 1. The similarity between the two curves shows that the spectral distributions on clear and overcast days are nearly the same, although the radiant powers are very unequal. The curves marked A and B in Fig. 2 were taken respectively before and after a heavy shower of rain, and show that there are variations which appear to depend less on the cloud cover than, for example, on the presence of water vapour or the form of the clouds.

(2.2) Haze, Thin Cloud and Mist

In Fig. 3 the full curve shows the average of 11 tests made on two winter days, cloudless but with a general haze, and 14 tests on three winter days with more than five-eighths of thin cloud (stratus and cirrostratus). The broken curve shows that the values of relative energy for the longer wavelengths are higher than for the clear-day average. Ground mist (Fig. 4) also appears to have the same effect.

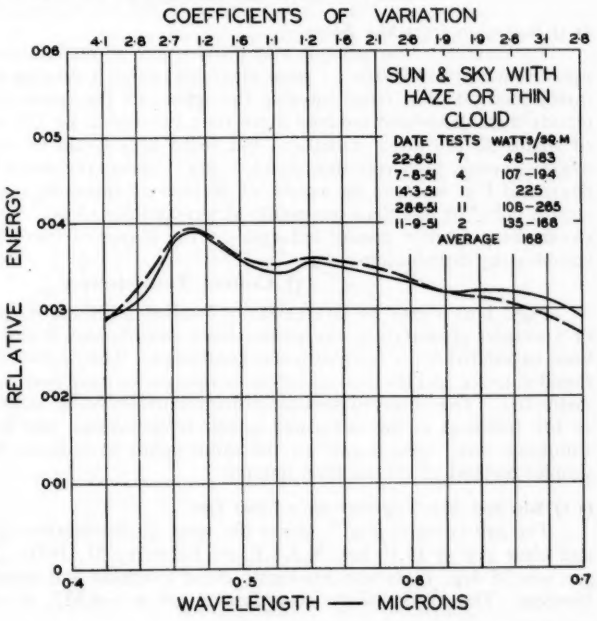

Fig. 3. Spectral energy distribution from sun and sky with haze or thin cloud.

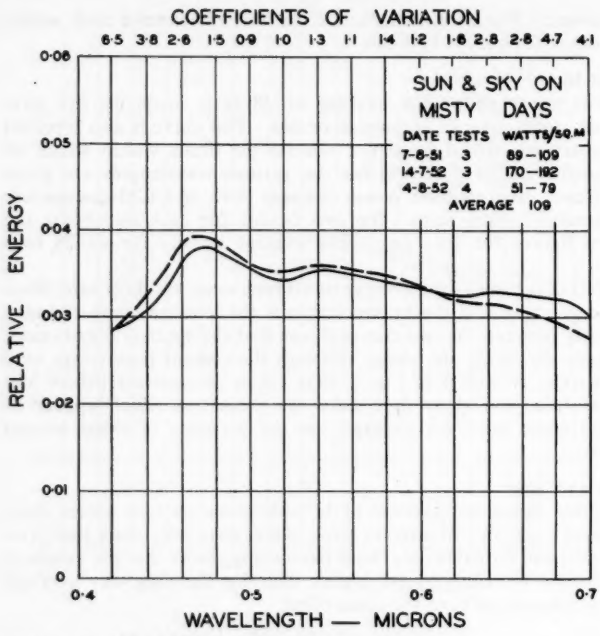

Fig. 4. Spectral energy distribution from sun and sky on misty days.

(2.3) Radiation from Sky Alone

To determine the amount and distribution of the radiation from the sky alone, measurements were made on some clear days using a shading disc which just prevented direct sun radiation from entering the sphere of the spectrophotometer. When the clouds were dense and covered more than one-eighth of the sky it was impracticable to shade off the direct radiation, but some tests could be made when the sky was wholly covered with very thin cloud. Fig. 5 shows the result of 17 tests on four clear days, and Fig. 6 shows the results of 10 tests on three days with some very thin alto-stratus cloud or less than one-eighth strato-cumulus cloud. As would be expected, the clouds have a much greater influence on the shapes of these distributions than on the sun-plus-sky distributions.

(3) Colour Temperature

Figs. 1 to 6 may be unnecessarily detailed for some purposes and as an example of a simpler presentation, the chromaticity co-ordinates in the 1931 C.I.E. system have been calculated for a few particular conditions. The co-ordinates lie close to the full-radiator locus, and the nearest colour temperatures have been calculated by MacAdam's method(2). The observed spectral distributions, however, differ appreciably from those of full radiators at the calculated colour temperatures, and in two cases the two distributions have been drawn on the same figure to indicate the variations which the simpler method of specification ignores.

(3.1) Sun and Sky Together on a Clear Day

The full curve in Fig. 7 shows the spectral distribution of radiation from the sun and clear sky at 11.10 hrs. N.Z.S.T. on February 21, 1951. The zenith angle of the sun was 35 deg., there was one-eighth cloud overhead and some smoke on the northern horizon. The chromaticity co-ordinates are $x = 0.327$, $y = 0.339$ and the nearest

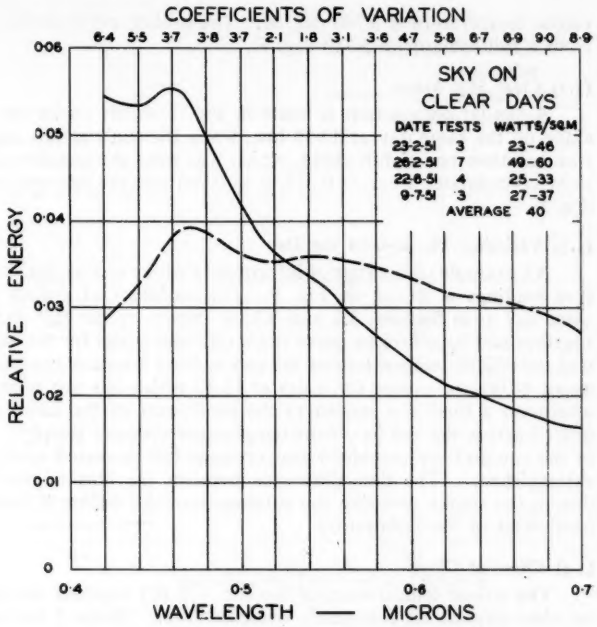

Fig. 5. Spectral energy distribution from sky alone on clear days.

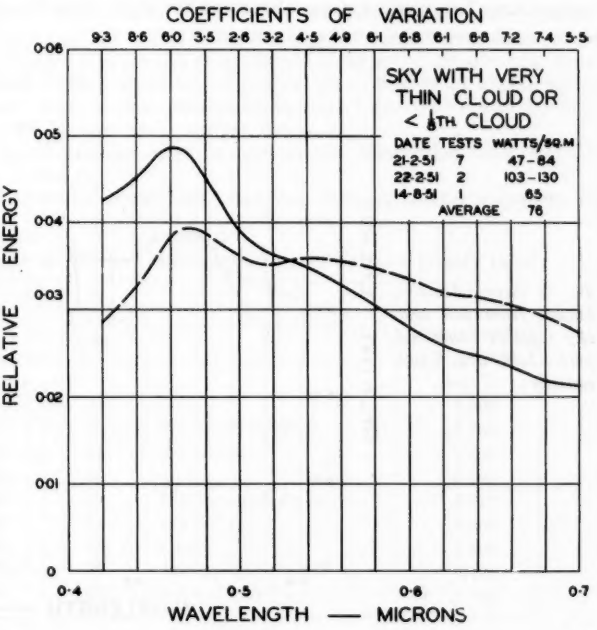

Fig. 6. Spectral energy distribution from sky alone with very thin cloud.

colour temperature is 5,740 deg. K. The broken curve shows the spectral distribution from a full radiator at 5,740 deg. K.

(3.2) Clear Sky Alone

A similar comparison is made in Fig. 8 which shows the radiation from the sky alone on the same day at 13.10 hrs., when the sun's zenith angle was 31 deg. There was less than one-eighth cloud, which was near the northern horizon. The chromaticity co-ordinates are $x = 0.272$, $y = 0.284$ and the nearest colour temperature 12,000 deg. K.

(3.3) Variation Throughout the Day

An example of the type of information which can be obtained from colour temperature readings is shown in Fig. 9. The variation of colour temperature during the same day as in Sections 3.1 and 3.2, is shown by the full curve for the sun and sky together and by a broken curve (on a different scale) for the sky alone. It will be seen that the colour temperature of the sun and sky together remained almost constant until about 14.00 hrs. except for a dip at 13.30 which has not been explained. During the afternoon a bush fire started to the south-west of the Laboratory and as the smoke drifted across the sky its colour temperature dropped steeply. The colour temperature of the sun and sky combined also dropped but increased again later when the fire was extinguished. The time difference between the dips in the two curves is probably due to the smoke covering the south-eastern sky before it reached the sun which was north-west of the Laboratory.

(3.4) Effect of Cloud

The colour temperature of the sun and sky together seems to be nearly the same on clear days as on completely overcast days. Table 2 lists several values of colour temperature for overcast days, also some for clear days for comparison.

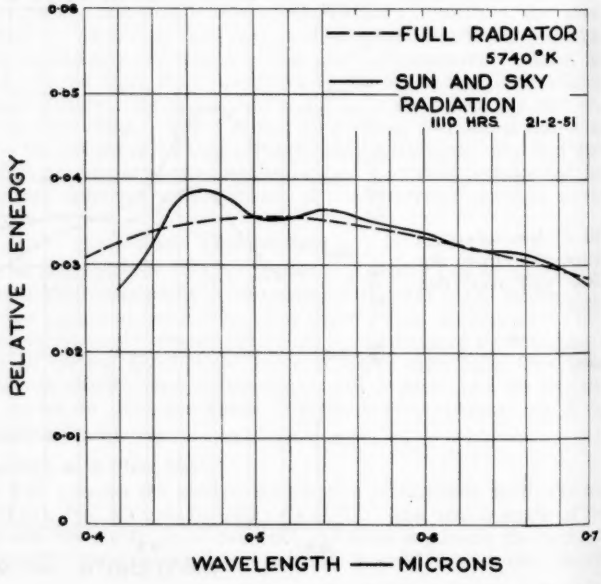

Fig. 7. Spectral distribution from sun and sky together compared with a 5,740 deg. K full radiator.

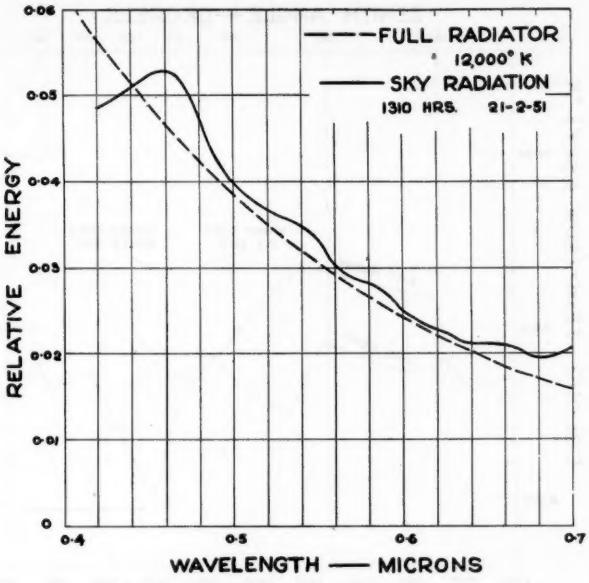

Fig. 8. Spectral distribution from sky alone compared with a 12,000 deg. K full radiator.

(4) Conclusions

For the settled weather illustrated in Figs. 1 to 4, the average spectral distribution of energy from sun and sky together varied little with cloud cover, whereas the average radiant power varied between 351 w/m² on clear days and 68 w/m² on overcast days. Haze, thin cloud, and mist slightly increase the proportion of energy at longer wavelengths, but other factors such as that illustrated in Fig. 2 (curves A and B) may introduce greater variations on apparently similar days.

Small amounts of cloud produce large changes in the distribution from the sky alone, as shown in Figs. 5 and 6.

It is not suggested that the results described are sufficiently comprehensive to

Table 2

Colour Temperature of Sun and Sky Combined on Clear and Cloudy Days

Date	Time NZST	Sun's Zenith Angle	Weather	Colour Temperature
	hrs.			deg. K
5/2/51	1450	38	Clear	5,890
9/2/51	1406	33	8/8 Ni.St. 1,500 ft.	5,700
9/2/51	1557	51	8/8 Ni.St.	7,400
16/2/51	1146	31	Clear	5,800
16/2/51	1319	30	8/8 haze and Cu.Ni.	5,710
16/2/51	1609	54	8/8 Cu.	5,990
22/6/51	1120	66	Clear	5,490
13/8/51	1139	57	8/8 Cu. and Cu.Ni.	6,100
7/9/51	1557	69	8/8 Cu. and Cu.Ni.	6,050

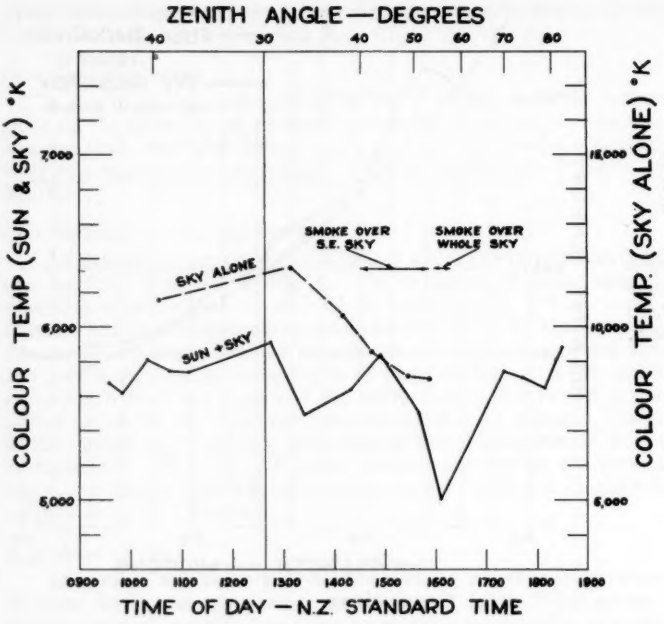

Fig. 9. Variation of colour temperature during the day.

enable precise limiting or average distributions to be forecast for all kinds of weather, but they should enable distributions for certain applications to be specified. For example, if it is desired to provide artificial lighting for growing plants which respond mainly to the amount of radiation supplied, a distribution similar to the clear-day average of Fig. 1 is likely to be suitable for a simulated environment, because that type of distribution occurs when the amount of radiation is great.

Acknowledgments

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(1) Taylor, A. H., and Kerr, G. P., J. Opt. Soc. Am., **31,** 3 (1941).
(2) MacAdam, D. L., J. Opt. Soc. Am., **33,** 18 (1943).

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